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Abstract. The penetrating power of X-rays coupled with the high flux of 3rd generation synchrotron sources makes X-ray tomography to excel among fast imaging methods . To exploit this asset of synchrotron sources is the motivation for setting up an ultra-fast tomography endstation at the TOMCAT beamline. The state of the art instruments at synchrotron sources offer routinely a temporal resolution of tens of seconds in tomography. For a number of applications, for example biomedical studies, the relevant time scales (breathing, heartbeat) are rather in the range of 0.5-2 seconds. To overcome motion artifacts when imaging such systems a new ultra-fast tomographic data acquisition scheme is being developed at the TOMCAT beamline. We can acquire a full set of projections at sub-second timescale in monochromatic or white-beam configuration. We present a feasibility study with the ultimate aim to achieve sub-second temporal resolution in 3D without significant deterioration of the spatial resolution. For the first time, the 3D dynamics of the very early stages of a quickly aging liquid foam can be visualised with high quality and sufficiently large field of view.

Keywords: fast tomography, imaging, in-situ, in-vivo, foams
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INTRODUCTION

During a tomographic acquisition, the sample must remain unchanged within the limits imposed by the spatial resolution of the reconstructed 3D volumes. If this condition is not satisfied motion artefacts arise, preventing the appropriate analysis (e.g. segmentation) of the images. There are two ways to go around this problem. The first is to ensure the stability of the sample and the second is to acquire the tomographic dataset faster. The first requirement may in some cases impair the study of interesting dynamical systems like liquid and aluminium foams, sintering of particles, breathing and heart cycle of animals. In certain systems, agents may be introduced to slow down their evolution and match the temporal resolution of the current tomographic capabilities. However this approach is often not possible and therefore an increase of the temporal resolution of the tomographic acquisition is required.

Ultra-fast radiography has been demonstrated at various beamlines [1,2,3,4] and a number of exciting applications has been successfully addressed [5]. Nevertheless the extreme demand on the mechanics, synchronisation and the detector prevents a straight-forward transition from 2D towards 3D ultra-fast imaging. With the following results we demonstrate that this important step can be achieved now.

The aim of this study was to prove the feasibility of high quality 3D imaging on systems with rapidly altering structure.

INSTRUMENTATION

There are 3 principal factors that determine the feasibility of ultra-fast tomography: (i) the brilliance of the X-ray source, (ii) the detector speed and sensitivity, (iii) the synchronization of acquisition. In the following we will address each of these elements.

The X-ray source of the TOMCAT beamline of the Swiss Light Source is a 2.9 TESLA superbending magnet. The photon flux at the exit of this source is of the order of 10^{13} photons/s/0.1%bw for a broad spectrum of photon energies of 15 to 22 keV [6]. The multilayer monochromator (Ru/C for energies of 8-21 keV or W/Si for higher energies up to 45 keV) provides a monochromatic beam with a bandwidth of 2% and reduces the photon flux by

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approximately two orders of magnitude. As a first step towards real-time tomography all the measurements here described have been performed with monochromatic X-rays at 20 keV, to exploit the high photon flux.

For high spatial resolution direct space imaging with frame rates above 100 Hz, the choice of the detection system is very limited. Although the development of new pixel detectors is approaching smaller pixel sizes and higher stopping power for hard X-rays, however these systems are not mature for tomographic microscopy. Visible light cameras coupled with lenses to a light conversion screen are currently the most suitable configuration. CCD based detectors with sufficient number of pixels (>2 Mpixels) have relatively long readout times despite advances such as the operation in frame transfer mode. With this, the choice of CMOS cameras for fast tomography is obvious. In this study, we used a demo version of the new pco.Dimax CMOS camera, coupled to a 300 μm thick YAG:Ce scintillator. The fluorescence curve of this scintillator (peaking around the value of 550 nm) was well matched to the maximum quantum efficiency of the camera (50% at 600 nm). The image formed by the scintillator was directly imaged to the camera chip using only a mirror and rely lenses. No microscope objective has been used in the current configuration, hence the effective spatial sampling of the image on the detector was 11 μm as given by the pixel size of the camera chip. A true 12 bit dynamic range operation of the camera is nearly achieved as the shot noise (including dark current and readout noise) was observed to be at a value of about 300 out of 4096 gray levels.

The angular speed and acceleration of the air-bearing rotation axis was calculated based on the frame rate of the camera set by the user. The rotation axis can rotate continuously at the selected speed and perform up to 100 turns limited by the controller. In this continuous mode, the camera is triggered automatically or by user signals to acquire one or more complete sets of projections corresponding to 180 degree rotation each.

To achieve 'synchronization of acquisition' we employ the strategy that a client distributes trigger signals to the camera and the rotation axis, ensuring a fully parallel acquisition.

EXPERIMENTAL RESULTS

Ultra-fast tomography has been performed on two kinds of samples. First on a trabecular bovine bone in absorption contrast mode, afterwards on two evolving liquid foams in edge enhancement mode.

Static Sample: Optimization of the Scan Quality

In order to evaluate the quality of the resulting 3D images we scaned a static sample (trabecular bone) with well known 3D structure. At 20 keV this sample gives good contrast in absorption mode.

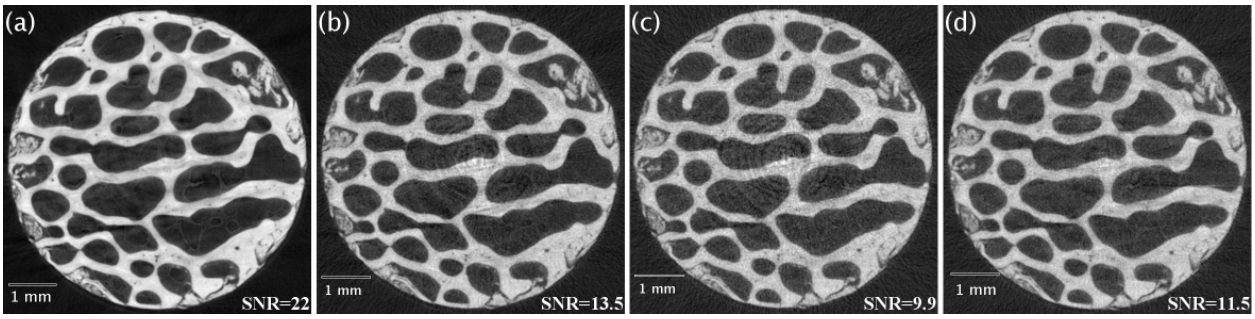

FIGURE 1. Comparison of tomographic slices from a biopsy of bovine trabecular bone obtained with 4 different acquisition protocols. (a) optimal illumination filling the 12 bit chip (exposure time, t_{exp}= 6 ms), moderate sampling (projections, N_{tomo}= 600), total scan time, t_{scan}= 3.7 s, (b) t_{exp}= 1.1 ms, N_{tomo}= 600, t_{scan}= 0.7 s, (c) short exposure, t_{exp}= 0.8 ms, N_{tomo}= 600, t_{scan}= 0.49 s, (d)) t_{exp}= 1.65 ms, minimal sampling, N_{tomo}= 300, t_{scan}= 0.49. All tomograms have been acquired at 20 keV photon energy, with the PCODimax camera in full frame mode (2016x2016 pixels) and pixel size of 11 μm.

The systematic study was carried out to evaluate the image quality for various scan parameters as depicted in Fig. 1. The figures of merit chosen for this purpose are the signal-to-noise ratio (SNR) and the spatial resolution. For our porpose it is sufficient to relate the SNR of the images on Fig. 1. rather than evaluate the SNR of the whole imaging system. If the SNR of the tomographic slice is defined by $SNR=(\langle I_{signal}\rangle - \langle I_{background}\rangle)/(\sigma^2_{signal}+\sigma^2_{background})^{1/2}$, where σ stands for standard deviation, we obtain SNR=22 (a), SNR= 13.5 (b),

SNR= 9.9 (c) and SNR= 11.5 (d). It means that improving the temporal resolution by a factor of 7.5 the SNR gets poorer by only a factor of 2. The spatial resolutions evaluated with two methods, the first based on the power spectrum of the images [7] the second by fitting the line profiles, does not show a trend similar to SNR. The spatial resolution remains uneffected at a value of about 2.5 pixels for all scans. By comparing figures 1c) an 1d) (same total scanning time) we conclude that when making compromises towards short scanning times, the reduction of the number of views has a smaller effect on the scan quality compared to the reduction in exposure time.

Liquid Foams: Evolution in 3D

The next goal was to visualize the evolution of a large number of individual bubbles forming a complex system. Two kinds of foams have been prepared ex-situ: a dry foam (~3% liquid fraction) and a wet foam (10-50% liquid fraction). In contrast to the previous sample, these liquid foams have to be studied using the phase shift of the X-rays rather than absorption. To switch from absorption to phase contrast imaging mode requires only to increase the distance between the sample and the detector, which allows interference of the X-rays. Adjusting the sample-to-detector distance to match the size of the first Fresnel zone to the detector pixel size provides images in edge detection regime. The films dividing the bubbles are too thin to be visualised, however the plateau borders are well defined and are sufficient to label individual bubbles [8].

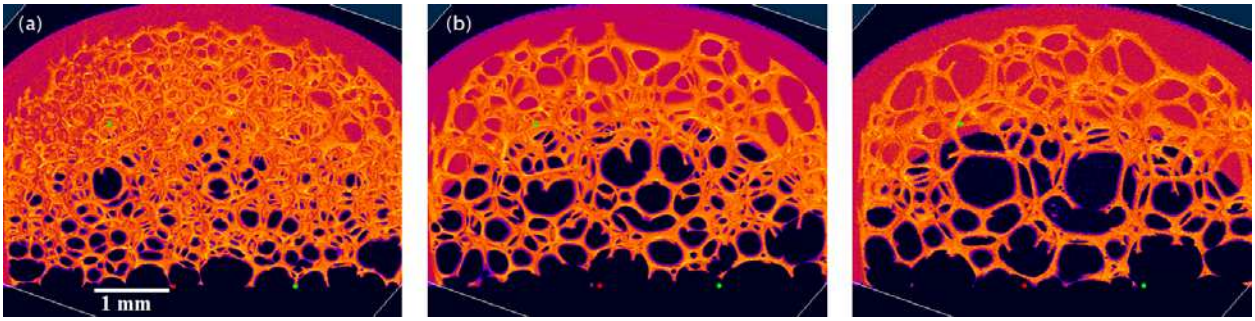

FIGURE 2. The 3D dynamics of a rapidly evolving liquid foam as visualised by the isosurface plots for t_0 (a), t_0+3 min (b), t_0+3.5 min (c).

In the case of the dry foam the surfactant was the substance in a common dish washing liquid solution. As stated in [8] the investigation of the evolution of the early stages of such foams has not been possible sofar without adding a stabilizer agent such as C_6F_{14}, routinely used in 3D studies to slow down the dynamics. We report a breakthrough in this matter: in spite of the rapid evolution of the foam (no stabilizer agent added), we show (Fig. 2) 3D reconstructions free of motion artifacts. The three images correspond to different stages of foam evolution all within the first 4 minutes after placing the foam on the tomographic stage (1-2 minutes after preparation).

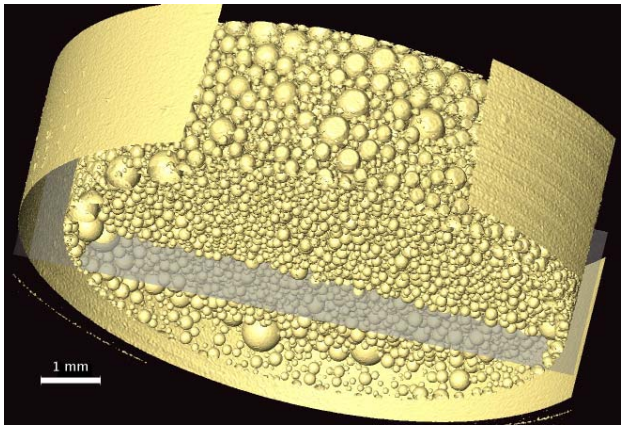

FIGURE 3. Volume rendering of an espresso foam with liquid fraction ranging from 10-50%. The bottom part of the 3D image shows the interface between foam and liquid coffee (the liquid phase is removed from the image). Total scanning time: 0.49 s.

The foam produced on the top of an espresso served as a representation of the wet foam model. The transition region between foam and liquid phase of the coffee sample is shown in Fig. 3. The image represents one volume out of the series of tomographic datasets with a temporal resolution better than 1 second. The wet foam tomograms serve as a demonstration that although the speed of the rotation axis is 360°/second, the centrifugal forces do not cause instability of the liquid sample.

CONCLUSIONS AND PERSPECTIVES

The TOMCAT superbend provides sufficient brilliance to enable exposure times as small as 1 ms or less for individual projections with monochromatic beam (highest flux for 15-21 keV), while the tomographic reconstructions remain of high quality. High spatial resolution (1-10 μm) requires the use of a microscope objective which in turn reduces correspondingly the number of photons arriving onto the camera chip. Omitting the multilayer monochromator, the flux increases by two orders of magnitude. Therefore even by employing optical magnification to achieve smaller pixel size, the concept of ultra-fast tomography is applicable at the TOMCAT beamline.

To further enhance the image quality of ultra-fast tomography, instead of using the YAG:Ce scintillator, LuAG:Ce crystals [9] will be used. They are now routinely installed for high resolution imaging at TOMCAT and show better efficiency for 10-22 keV than the YAG:Ce scintillator.

One goal of the real-time tomography project at TOMCAT is the visualization of the acquired 3D volume or its part at rates comparable to the total acquisition times. For this purpose, fast tomographic reconstruction procedures are being developed [10] with the potential to allow 3D visualisation synchronized with the acquisition. The reconstruction algorithm based on the Fourier Transform method and implemented to the Graphical Processing Unit reduce the reconstruction time of one tomographic slice with 4Mpixels down to 0.5 s on a single CPU.

For three-dimensional high spatial resolution in-vivo imaging, the most promising probe is x-rays [11]. The experimental results presented here clearly indicate that this technique has reached maturity to address in-situ studies of different kind as well as the physiology of small animals in 3D using X-ray attenuation or phase shift as contrast mechanism.

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